

# Microbial fuel cells utilising carbohydrates

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**Abstract:** The paper reports results of a mediatorless microbial fuel cell (MFC), utilising waste carbohydrate (manure) as a fuel, which did not use a catalyst or a proton exchange membrane and is thus environmentally friendly (by using no toxic substances) in treating waste. The cell used a manure sludge in the anode compartment and an aqueous salt solution (seawater) containing dissolved oxygen. The influence of the geometric position of the anode and cathode, both made of carbon cloth, had a major effect on the fuel cell power performance. The maximum power density obtained with the cell was  $4.21 \text{ mW m}^{-2}$ . The paper also reports results of a mediated MFC using a yogurt bacteria and methylene blue as mediator. This cell produced a maximum power density of over  $13 \text{ mW m}^{-2}$ . This power output compares quite favourably with that achieved with the same cell using glucose as fuel with *E. coli* (peak power density of  $180 \text{ mW m}^{-2}$ ).

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**Keywords:** microbial fuel cell; mediators; mediatorless; carbohydrate waste; yogurt; manure

## INTRODUCTION

Biological fuel cells convert the chemical energy of carbohydrates, such as sugars, directly into electric energy. The interest in biological fuel cells is that they operate under mild reaction conditions, namely ambient temperature and pressure, and use inexpensive catalysts, i.e. microorganisms or enzyme. There are two types of biological fuel cells, namely microbial fuel cells (MFCs) and enzymatic fuel cells. A problem with most redox enzymes is that they do not take part in direct electron transfer with conducting supports. Hence electron mediators are used for the electrical connection of the biocatalyst and the electrode. Several methods have thus been used to functionalise the electrode surface with layers consisting of redox enzymes, electrocatalysts and biocatalysts that promote electrochemical transformation at the electrode interface.<sup>1</sup> An alternative to redox enzymes is the use of microorganisms in biological fuel cells, which eliminates the isolation of individual enzymes, thereby providing cheaper substrates for biological fuel cells. The field of biological fuel cells including MFCs has been the subject of several reviews.<sup>2–4</sup>

The use of microorganisms in biological fuel cells eliminates the isolation of individual enzymes, thereby providing cheaper substrates for biological fuel cells.<sup>5</sup> Microorganisms that require a mediator do not have electrochemically active surface proteins to transfer electrons to the anode electrode. MFCs that do not use mediators still require some form of carbohydrate to function, whether the fuel cell is single culture

or not. Metal-reducing bacteria, e.g. Geobacteraceae family and *Shewanella* genus, are the most used species in this type of fuel cell. These organisms can reduce many substrates, such as Fe(III).<sup>6,7</sup> However, the range of electron donors that these organisms can use is limited to simple organic acids such as acetate. In one study by Bond and Lovely,<sup>8</sup> it was shown that *Geobacter sulfurreducens* provides 3000-fold increase in electron activity in comparison to other organisms such as *Shewanella putrefaciens*. This latter organism can also operate in mediatorless fuel cells as well as with mediated fuel cells and can utilise wastewater.<sup>9</sup>

MFCs that use *S. putrefaciens* are more established than those that use organisms of the Geobacteraceae family. Geobacteraceae have been shown to outperform the *Shewanella* genus, but *Shewanella* is a more established organism in MFCs, which also has application in the biosensor industry.<sup>10</sup> In the Korean Institute of Science and Technology (KIST), functioning MFCs that use *S. putrefaciens* have been constructed. Like the Geobacteraceae family, *S. putrefaciens* can reduce a wide range of substrates including Fe(III).<sup>9</sup> Fe(III) reduction is important as Fe(III) acts as an electron acceptor in anaerobic respiration, in particular with regard to c-type cytochromes, which are surface active and responsible for electron transfer to the anode.<sup>11</sup> However, *S. putrefaciens* and Geobacteraceae are not the only organisms capable of Fe(III) reduction with surface-active cytochromes. *Clostridium beijerinckii*, *Clostridium butyricum*, *Desulfotomaculum reducens*, *Rhodobacter capsulatus*, *Thiobacillus ferroxidans* and even the *Geovibrio* genus are all capable of

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use in a mediatorless fuel cell as the organisms, some of which were isolated from a fuel cell using starch wastewater.<sup>12,13</sup>

The marine environment provides a good example of a mediatorless MFC. Tendler *et al.*,<sup>14</sup> in association with the US Office of Naval Research, have created a fuel cell using the different sediments on the sea floor. The concept of a sediment fuel cell is relatively simple: two carbon electrodes placed in two different environments. One electrode is placed in the anoxic sediments and the other placed in the seawater immediately above the sediment. The resulting voltage gradient is sufficient to generate power. Power output is not as high as in some other MFCs, such as that described by Bond and Lovely.<sup>8</sup> The peak power density of the sediment fuel cell is around  $30 \text{ mW m}^{-2}$  with a current density of around  $75 \text{ mA m}^{-2}$  and a voltage of 400 mV. The interesting aspect of the sediment fuel cell is that there are no expensive precious metals acting as catalysts, therefore making this type of fuel cell relatively inexpensive, not taking into account the cost of locating the fuel cell on the sea floor.

The mediatorless fuel cells have an advantage over those with mediators in terms of cost as well as the absence of undesirable toxic mediators. A number of authors have reported using mediatorless MFCs. Successful systems have been constructed without expensive selective membranes, mixed communities have been successfully exploited in a number of MFC and, most recently, electricity has been generated using complex energy sources, including wastewater. The power outputs of MFC are generally low and variable. With complex substrates the reported power in MFCs is in the range of  $10\text{--}146 \text{ mW m}^{-2}$ , while with defined media the reported range is rather greater:  $0.3\text{--}3600 \text{ mW m}^{-2}$ . This is a very large range indeed; the upper value coincided with almost 90% coulombic efficiency: i.e., 90% of the added substrate was converted to electricity.

There are a number of reasons why less than perfect coulombic efficiency or low power might be observed: these include the efficiency of the anode, the efficiency of the cathode and the presence of competing electron acceptors. It is evident from the literature that anodic efficiency and the microbial composition of the electrophilic community at the anode are particularly important.

For example, when Park and Zeikus<sup>15</sup> attempted to raise anodic efficiency by impregnating the anode with a mediator, they raised the power density from  $0.44 \text{ mW m}^{-2}$  (in an unimproved reactor) to  $91 \text{ mW m}^{-2}$  (with the adapted electrode) while using *Escherichia coli* as the microbe. However, when the pure culture of *E. coli* was replaced with sewage sludge the power density in the improved reactor rose to  $788 \text{ mW m}^{-2}$ . This would suggest that sewage sludge fortuitously contains efficient electrophilic organisms. One might further deduce that such electrophilic organisms would be at a selective advantage in

an MFC. This is evident from the work of Jang *et al.*,<sup>16</sup> who fed artificial wastewater to sewage sludge in a novel membraneless mediatorless flow-through reactor and observed the current to increase 20-fold over a 30-day period, presumably reflecting the selection of favourable organisms (though the ultimate power density was just  $1.3 \text{ mW m}^{-2}$ ). This line of reasoning is carried to its logical conclusion by the work of Rabaey *et al.*<sup>17</sup> Using a simple unimproved electrode they achieved a power density of  $3600 \text{ mW m}^{-2}$  and 90% coulombic efficiency by passing sludge from an anaerobic digester through a series of five glucose-fed batch reactors.

Improvements in microbial fuel cell performance have been made by considering aspects of improved reactor designs and incorporating alternative air cathodes to platinum that thus reduce the cell cost.<sup>18</sup> Alternative substrate fuels have also been considered such as swine wastewater, which owing to the higher concentration of organic matter produced greater power densities than that achieved with domestic wastewater.<sup>19</sup> In the context of using alternative fuels we report data of the performance of an MFC which uses manure as the fuel.

## EXPERIMENTAL

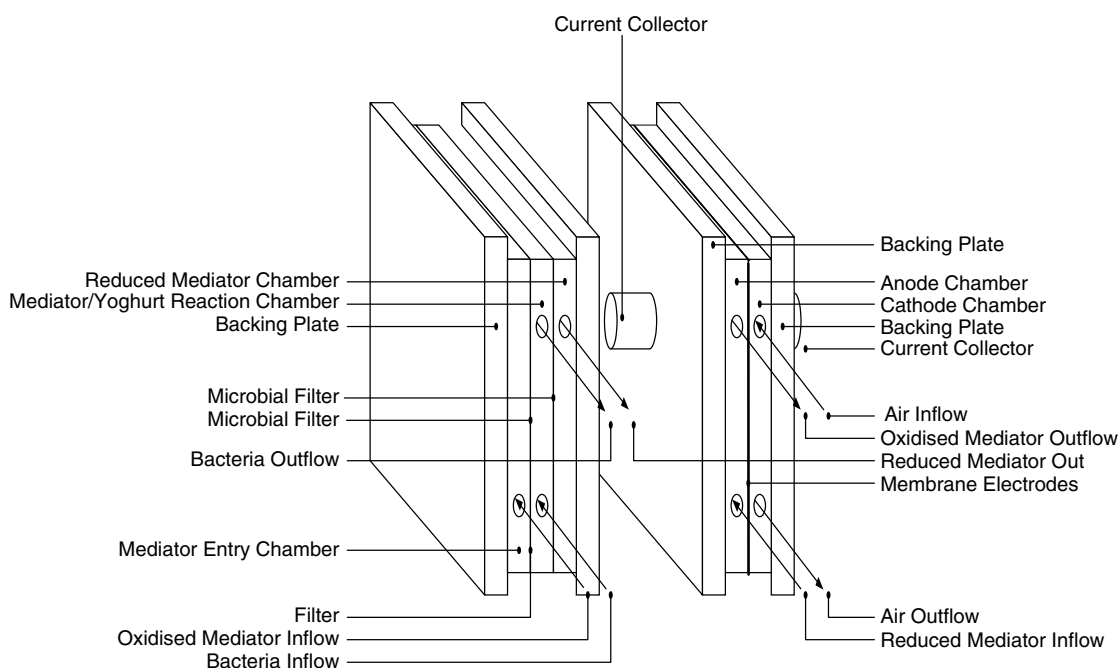
In this work two MFCs were used: one which used a mediator and a proton-exchange membrane to separate the anode and cathode compartment (mediator cell), and the second which was mediatorless and did not use an ion-exchange membrane.

### Mediator cell

The mediator fuel cell is shown in Fig. 1. This fuel cell design included the use of pressed membrane electrodes, stainless steel mesh for current collection, with a threaded stud collecting the current from the mesh. A platinum/oxygen cathode was employed because of its high efficiency as an electron acceptor. The cathode was covered with carbon paper, wet proofed with Teflon (20%) (E-Tek TGPH 120 Toray; E-TEK, Somerset, NJ, USA). The anode used was also made from carbon paper (E-Tek TGPH 120 Toray).

The MFC was constructed using methylene blue or 2-hydroxy-1,4-naphthoquinone ( $1.0 \text{ mol L}^{-1}$  concentrations) as the mediator, and glucose or yogurt as the fuel.

The system used a closed-loop feed system which included the bacteria and mediator circulating from a sealed 250 mL conical flask of *E. coli* in minimal media with  $0.5 \text{ mol L}^{-1}$  glucose (C source) in a constant-temperature bath at  $37^\circ\text{C}$ . Air was piped into the cathode from an air cylinder at  $1 \text{ dm}^3 \text{ min}^{-1}$  and the air exit of the cathode discharged into a conical flask of water. The potential was measured using a digital multimeter. A power supply was used to apply load to the fuel cell through a



**Figure 1.** Microbial fuel cell using reduced mediator. The mediator entry chamber has methylene blue entering and flowing through a microbial filter into the reaction chamber, where the mediator is reduced by the bacteria present in the yogurt. The mediator then flows through another high-volume glass fibre filter into the reduced mediator inflow in the second part of the fuel cell. The mediator is then oxidised at the electrode surface.

variable resistor which was measured through another multimeter.

The bacteria used were either *E. coli* or yogurt bacteria. *E. coli* was grown on nutrient agar plates. The *E. coli* contained no antibiotic-resistant genes and was not modified in any way. Stocks were maintained on nutrient agar slopes. The cells were then grown in 250 mL nutrient broth and harvested in growth phase for use in the fuel cell. Nutrient agar and nutrient broth were purchased from Sigma-Aldrich (Poole, UK): nutrient broth product number 70 149 and nutrient agar product number 70 148, respectively. Both were made to the manufacturer's instructions.

Yogurt bacteria were used to obtain power from diary milk. The yogurt source was Danone live bacterial culture. Experiments were set up where the mediator (methylene blue) was passed through live yogurt, filtered (through a high-volume glass fibre filter) and then pumped into the anode chamber, creating the concept that a reduced mediator was the 'fuel' to the cell. The mediator entry chamber had  $10 \text{ mmol L}^{-1}$  methylene blue entering and flowing through a microbial filter into the reaction chamber, where the mediator was reduced by the bacteria present in the yogurt. The mediator then flowed through another high-volume glass fibre filter into the reduced mediator inflow in the second part of the fuel cell. The mediator was then oxidised at the electrode surface in the same way as a normal microbial fuel cell.

Potentiostatic measurements were made using a standard electrochemical 'H' cell to determine the

influence of the bacteria on the anode response to mediator.

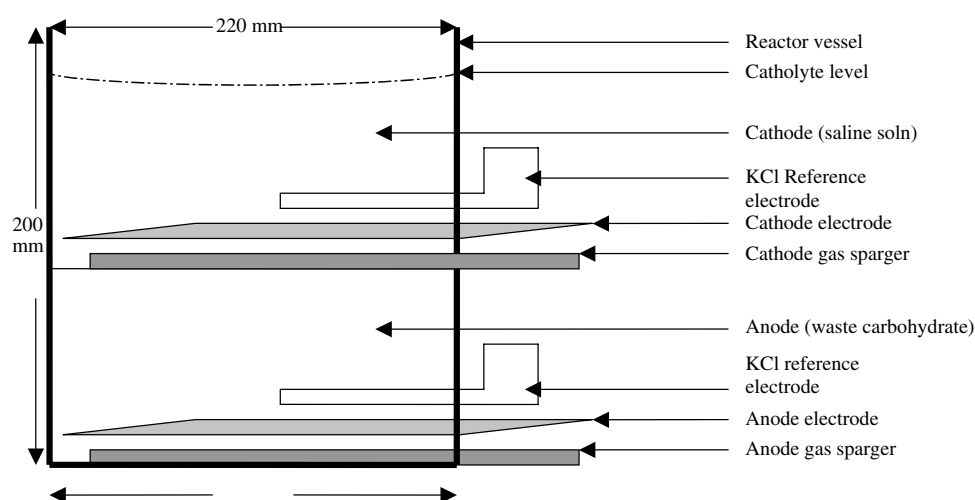
### Mediatorless MFC

#### Fuel cell feed

William Sinclair (Lincoln, UK) dried blended farm manure was used (available commercially in garden centres) as the fuel, selected on the basis that it was not sterilised but only dried and therefore could be reactivated by hydration and incubation. The amount of dried manure in the majority of cells was 3 kg and it was hydrated until a thick slurry was obtained. A nylon cloth separation layer was placed on top of the slurry and sealed to the edge with silicone sealant. An airtight plastic sheet was placed on top of the nylon layer (once the previous silicone layer had cured) and sealed on top with silicone. Space was left between the plastic sheeting and the nylon separator to allow biogas formation under the sealed layer. Prior to testing as a fuel cell the reactor was placed in an incubator at  $37^\circ\text{C}$  for one week to allow the formation of an anaerobic environment in the anode. The build-up of biogas from carbohydrate digestion could be seen after 2–3 days of incubation. The cell was left incubating for one week to allow for a complete anaerobic environment to form.

#### Fuel cell design

The fuel cell reactor was tested initially as a batch system, similar to a battery. The reactor was constructed from a modified 7 L laboratory sharps cylindrical incineration bin manufactured from ABS plastic. The fuel cell contained horizontally positioned electrodes as shown in Fig. 2. The electrodes were



**Figure 2.** Schematic of mediatorless microbial fuel cell.

made from Ballard (Vancouver, Canada) Avcarb 1071HCB woven carbon cloth, cut into circular pieces. All electrodes had a cross-sectional area of  $256\text{ cm}^2$ . This material was used as gas diffusion layers in standard polymer electrolyte fuel cells with hydrogen gas as fuel. The carbon electrodes were electrically connected to the load outside of the reactor by means of a hole in the side of the reactor sealed with silicone. Antifouling electrodes were not used as it was desired to encourage biofilm formation to allow electrical conductivity between the substrate and electrode due to the electrochemically active nature of biofilms.<sup>20</sup> Also, as the final fuel cell was intended to have flow of fuel and oxidant over the electrodes, natural sloughing off of biofilm would probably occur.

The manure slurry was placed on the bottom of the reactor; in which was located the anode. The cathode was placed above the manure in water. Non-sterilised seawater was used as a catholyte, as it is more conductive than sterile water. The reactor also contained gas spargers for the supply of gases (air, nitrogen, carbon dioxide). The spargers were constructed from hard plastic tubing with four 1 mm holes around the tube drilled at 1 cm intervals.

Also incorporated into the cell were lugin capillaries connected to a reference electrode via a KCl salt bridge to measure individual electrode potentials.

#### *Fuel cell test procedure*

On the initial construction of a cell, the open cell voltage (OCV) was monitored. When a stable OCV was reached and maintained for 48 h, testing on the cell commenced. The potential was measured using a digital multimeter. To measure the power output of the cell, i.e. to obtain cell polarisation data of potentials *versus* current, a power supply was used to apply load to the fuel cell through a variable resistor. The resulting potential, measured through another multimeter, provided the value of the current. Once a single fuel cell had been constructed and an initial test carried out with air in the cathode and nitrogen in

the anode, a programme was devised to test different variables of electrode positions (Fig. 3).

The fuel cell was set up as a battery so that power output could be established without concerns about fuel delivery. The data gathered would form the basis for later comparisons and for future optimisation of the system for subsequent studies. The cell described above was tested in the following ways, once it was established that gas flow was not desirable:

- Cell 1: The original cell with no air in the anode and no nitrogen in the cathode.
- Cell 2: An increase in the distance of the cathode from the anode, and bringing the cathode nearer the surface of the water, which should also aid oxygen transfer to the cathode.
- Cell 3: A smaller distance between the anode and the cathode to examine the effect of relatively close proximity of anode and cathode.
- Cell 4: This cell examined the effect of positioning the anode closer to the cathode and the cathode nearer the surface of the catholyte on the overall performance of the cell.

#### *Carbohydrate utilisation*

Each cell was assessed to see if the output from the cell was a result of carbohydrate utilisation in the fuel, using a simple calorimeter. A sample of manure was taken from each cell and a sample of unused manure as a control, and both were dried in an oven at  $60^\circ\text{C}$  to remove all water vapour. 1 g of manure was used in each test.

#### *Bacterial colonisation of electrode*

The bacteria in biofilm formation function by enabling the direct transfer of electrons to the anode surface. An environmental electron microscope, which allows samples to be examined while still wet, was used to analyse the surface of the electrodes for bacterial colonisation/biofilm.

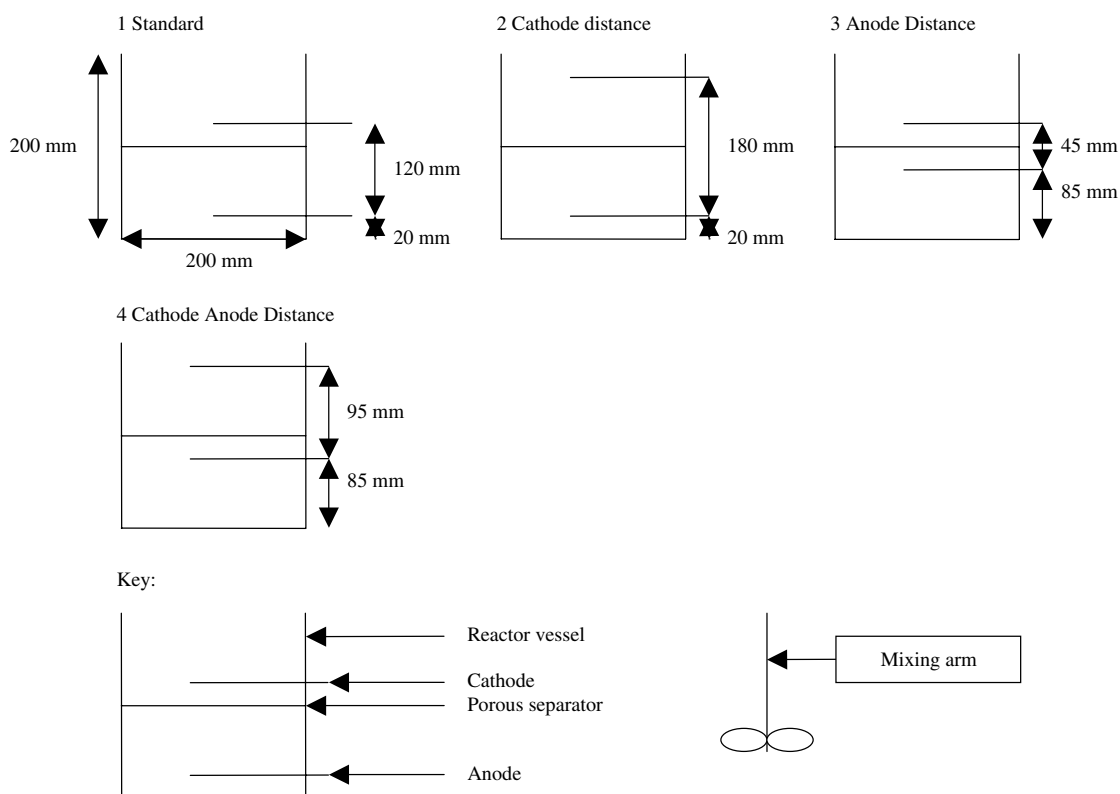


Figure 3. The different electrode positions in the mediatorless fuel cell to allow optimisation of the cathode, anode, fuel mass and catholyte.

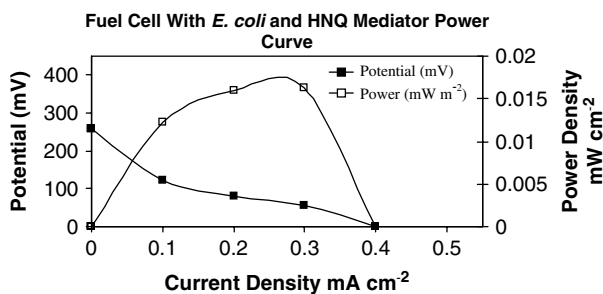


Figure 4. Potential and power density performance of an MB-mediated fuel cell.

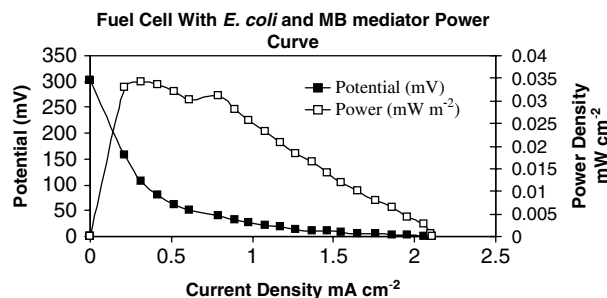


Figure 6. Potential and power density performance of an HNQ-mediated fuel cell.

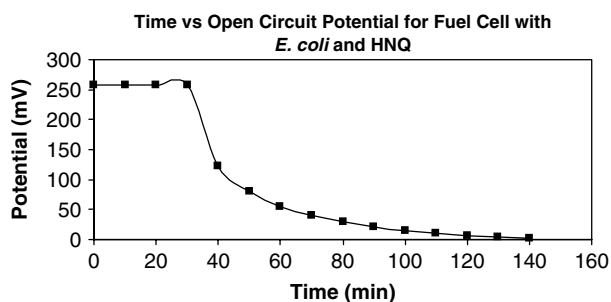


Figure 5. Potential time variation of an MB-mediated fuel cell.

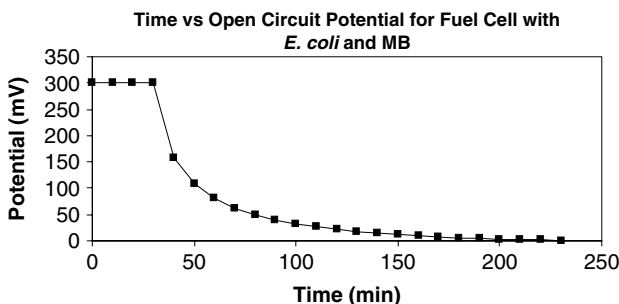


Figure 7. Potential time variation of an HNQ-mediated fuel cell.

## RESULTS AND DISCUSSION

### Mediated MFC

Figs 4 and 6 show the typical cell potential *versus* current density plots of the mediator MFC, and Figs 5 and 7 show the variation in open circuit potential with time for the MFCs using the two different mediators. The open circuit potential with methylene

blue (MB) and hydroxy-naphoquinone (HNQ) were 300 mV and 260 mV, respectively. As can be seen from Figs 4 and 6, *E. coli* is more effective with MB due to the higher power output achieved: approximately 0.018 mW cm<sup>-2</sup>. Also MB gave a longer duration of

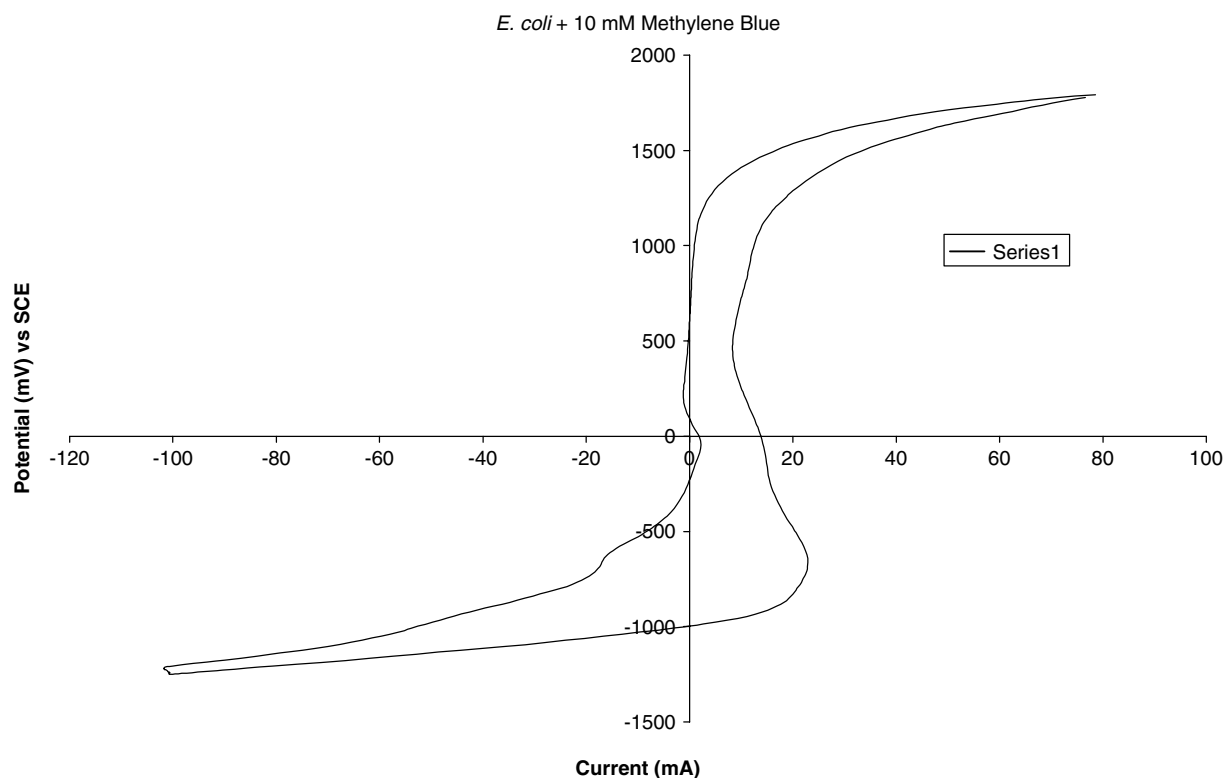


Figure 8. Cyclic voltammogram of MB with *E. coli*.

cell performance and consequently it was used in the MFC using yogurt bacteria.

To check that MB was taking part in the reaction, the absorbance of methylene blue at its peak absorbance, using a Unicam 8700 UV-visible spectrophotometer, was used to analyse the state of oxidation and reduction of the mediator. The media that flowed through the fuel cell reduced the size of the peak absorbance at 660 nm and after full spectral scans it was possible to see that 660 nm was still the point of peak absorbance and all peaks had been reduced.

Potentiostatic measurements, using cyclic voltammetry, to determine the influence of the bacteria on the anode response to mediator are shown in Fig. 8. The data show that there is a clear reversible reaction of MB in the presence of *E. coli*, which is necessary for fuel cell operation. Hence MB was used as the more effective mediator in the yogurt fuel cell. Initial tests with the yogurt culture in the fuel cell did not realise any significant power performance.

Figure 9 shows the typical variation of open circuit potential using the yogurt bacteria MFC. The fuel cell had an initial OCV of 160 mV, which began to fall after 2 days of operation. The peak power density of the fuel cell was  $0.0013 \text{ mW cm}^{-2}$ . The performance of the yogurt fuel cell was clearly inferior to that of the fuel cell using glucose as the fuel. This system theoretically eliminates the problem of bio-film formation. The filtration system used a high-flow/volume glass fibre filter. However, drawbacks with the fuel cell were related to operation with the filtration system, which continually clogged, and also the use of the perishable

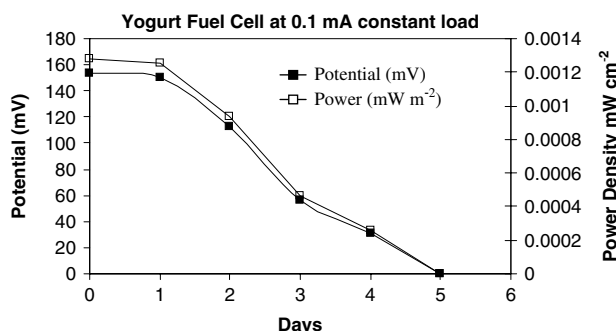


Figure 9. Potential and power density of the cell over a 5-day period.

substrate (milk); making long-term use of the fuel cell difficult.

### Mediatorless MFC

A series of fuel cell tests were performed to determine the effect of some geometric parameters (anode and cathode location) on the power performance. The temperature of the fuel cells was the room temperature of the laboratory, normally  $20^\circ\text{C}$ , during daytime tests. The cells were subject to overnight cooling when heating in the laboratory was switched off. It was impractical to try to maintain the temperature of the cells constant due to equipment constraints and the fact that cells were tested simultaneously. Furthermore, it was felt appropriate to test the cells under conditions that would more closely mimic those of a practical MFC using waste, with variable temperature during day and night. The typical test duration of the fuel cells was 30 days. The data

presented below were the average of a series of polarisation tests carried out daily on the cells.

In initial tests it was found that when nitrogen was added to the cathode the fuel cell could not sustain any load, as was the case when air was added to the anode. This provided evidence that the fuel cell was driven by an anaerobic reaction in the anode and an aerobic reaction in the cathode. Normally gas sparging is expected to increase mass transfer. In the MFC, addition of nitrogen to the anode reduced the power output because it disturbed mass transfer of bacteria contacting the anode, by bubbling over the surface of the anode (also through the woven cloth anode) and reducing contact between the anode and fuel.

Adding air to the cathode also reduced the power output, which did not conform to what may be expected in practice for improvement in cathode polarisation. It is suggested that the anaerobic environment is disturbed by the air, as the addition of air should increase the performance of the cathode. In addition, the gas bubbles may also have caused some 'blinding' of the cathode surface.

The data obtained in cell 1 are shown in Fig. 10. The open circuit potential was 410 mV, which fell on applying a load, due to electrode polarisation. The maximum current density achieved was just less than  $40 \text{ mA m}^{-2}$  at a cell voltage of zero. There was an apparent rapid fall in potential at around 270 mV. This rapid fall in potential was seen in much of the data generated under different test conditions, although at the moment we are not clear as to the cause of this effect. The cell had a peak power performance of over  $4.0 \text{ mW m}^{-2}$ .

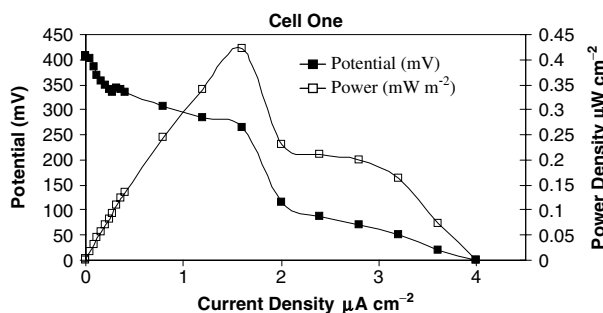


Figure 10. Cell voltage and power density performance of cell 1.

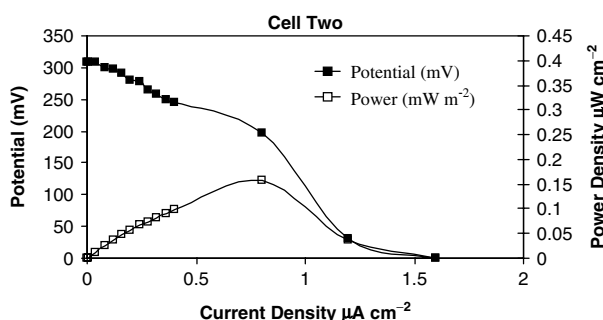


Figure 11. Cell voltage and power density performance of cell 2.

Figure 11 shows the data obtained from cell 2, in which the distance of the cathode from the anode was increased. This cell brought the cathode nearer to the surface of the water and would have been expected to aid oxygen transfer to the cathode. The open circuit potential for this cell was lower than that of cell 1 and may reflect the inherent variability in power performance that an MFC might show during operation. However, the maximum current density this cell gave was around  $15 \text{ mA m}^{-2}$ , with a peak power performance less than half that of the control ( $1.6 \text{ mW m}^{-2}$ ). A possible reason for the lower performance is that positioning the cathode further away from the anode exposed the anode to greater concentrations of oxygen from the water above the manure (supplied by diffusion). In addition, there will be some small effect from the increased ionic resistance between the two electrodes. A desired effect of improving cathode oxygen reduction by reducing the diffusion distance for oxygen from the surface was not seen.

Figure 12 shows the effect of decreasing the anode and cathode distance by bringing both electrodes close to the interface of the manure and water. In this case there was only a small reduction in the OCV compared to cell 1. The maximum current density achieved was  $25 \text{ mA m}^{-2}$  and the peak power was  $1.3 \text{ mW m}^{-2}$ . This lower power density compared to that achieved in cell 1 was a result of the initial, quite rapid fall in potential on applying a load. The poor performance could be due to bringing the anode into closer proximity to the water containing air.

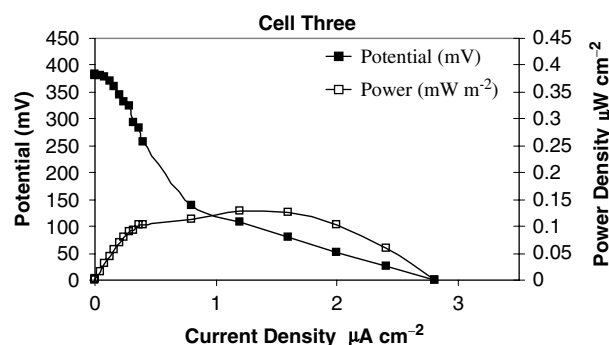


Figure 12. Cell voltage and power density performance of cell 3.

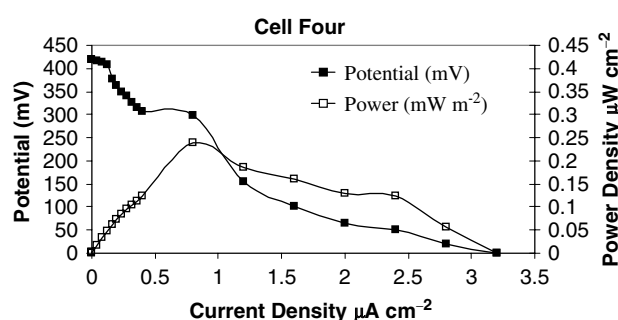


Figure 13. Cell voltage and power density performance of cell 4.

Figure 13 shows the cell performance with the anode close to the manure/water interface and the cathode close to the water/air interface. The OCV and maximum current are similar to those achieved with cell 1. In this case, having the anode closer to the cathode and the anode nearer the interface with the catholyte did not improve performance of the cell compared to the control. The peak power density was reduced to around  $2.5 \text{ mW m}^{-2}$ . Compared to the control cell, cell 4 would benefit from the closer proximity of the cathode to the water–air interface but also would be affected (polarised) more by the closer proximity of the anode to the slurry water interface.

While there are a few well-known methods of constructing high-performance MFCs,<sup>1</sup> the research carried out shows that a novel low-cost and relatively simple fuel cell can be designed using the features of a cell without a proton-exchange membrane, single-culture organisms and no precious metal catalysts. Clearly the influence of the geometric position of the anode and cathode has had a major effect on the fuel cell. In future work we will explore the effect by trying to monitor the individual electrode potentials. Initial attempts to do this were beset with problems of blockage of the lugin capillaries.

Ongoing work at Newcastle is addressing the important issues of cell design and electrode materials, in which a number of alternative anodes and cathode catalysts will be examined. From experience in more conventional fuel cell systems cathode catalysts which offer much reduced electrode polarisation are being examined and include materials based on iron, manganese and metal porphyrins (Fe, Co TMMP).

#### Carbohydrate utilisation

To assess the extent of carbohydrate use in the fuel cell, simple calorimetry measurements of the energy content of the fuel after use were made. Table 1 shows the energy ( $\text{kJ g}^{-1}$ ) left in the manure after the cells had been tested. The control was freshly hydrated manure that had not been used in a fuel cell. It can be seen that in all the cells that there was a significant drop in calorific value from the control, which shows that the manure had been digested in every cell with between 90% and 98% utilisation. The pH changes in the manure for each test cell were also very similar (Table 1).

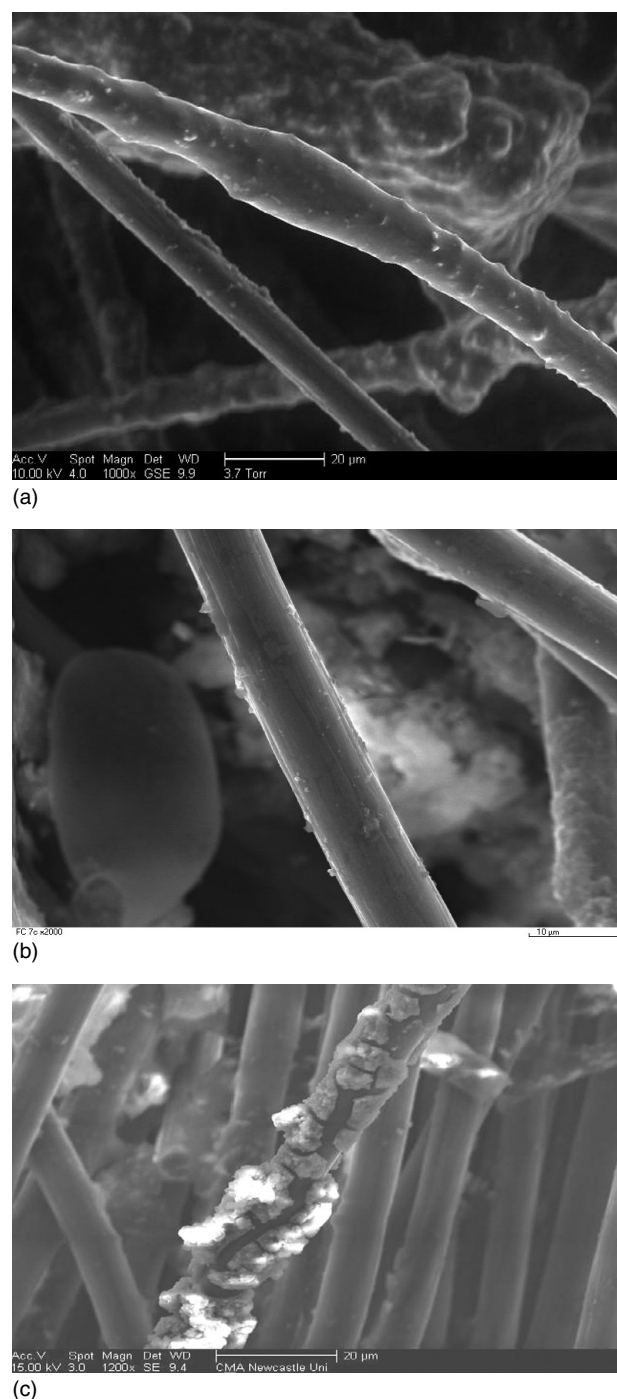
**Table 1.** Calorific values of manure in Test cells after use

Sample	$\text{kJ g}^{-1}$	Increase in anode pH (final pH)
Control	82.0	
Cell 1	3.14	+0.89 (7.3)
Cell 2	5.65	+0.80 (7.4)
Cell 3	1.88	+0.86 (7.3)
Cell 4	1.88	+0.99 (7.53)

#### Bacterial colonisation of electrodes

After the cell polarisation tests electrode samples ( $3 \text{ cm}^2$ ) were cut from the anodes, great care being taken not to disturb biological material from the carbon cloth, to examine the bacterial colonisation of the electrodes and bio-film formation with a scanning electron microscope (SEM).

Figure 14 shows typical SEM images of the anode surfaces where microbial colonisation is quite clearly shown on the electrodes. The most visible biomass is in the cell that had the highest power output and can



**Figure 14.** SEM of carbon fibre anode: (a) cell 1 after cell polarisation test; (b) cell 2 after cell polarisation test; (c) cell 3 after polarisation test.

be confirmed by contrasting the SEM images of cell 1 (Fig. 14a) with cell 2 (Fig. 14b).

Figure 14(c) shows the colonisation of cell 3, the worst-performing cell from the parametric study (peak power  $0.13 \text{ mW m}^{-2}$ ). Some bio-film is visible in the background of the picture but the majority of fibres were uncolonised. The bio-film shown has cracked due to the drying effect of the vacuum in the sample chamber of the SEM. Great care was taken when dissecting the electrodes not to disturb any bacterial structures. Structures such as those to the centre left of the image would be disturbed when gas, e.g. nitrogen, is bubbled through the anode, resulting in a loss of power and OCV.

## CONCLUSIONS

The feasibility of operating a microbial fuel cell with manure has been demonstrated using a simple 'batch' cell. The cell used a stationary pool of manure sludge covered by a layer of water into which oxygen transfer occurs by natural diffusion. Thus it has been shown that a fuel cell can be constructed with the environment in mind as well as keeping costs down. It has also been shown that the MFC is not dependent upon mediators, proton-exchange membranes, single-culture organisms or precious metal catalysts. To minimise costs and to make a more durable cell, precious metals were avoided; however, the research does recognise the benefits of using precious metals or other catalysts for the cathode. Mediators were avoided due to their increased toxicity and to reduce addition of chemicals to the cell.

## ACKNOWLEDGEMENTS

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## REFERENCES

- Shukla AK, Suresh S, Berchmans S and Rajendran A, Biological fuel cells and their applications. *Curr Sci* **87**:25–468 (2004).
- Palmore GTR, Bioelectric power generation. *Trends Biotechnol* **22**:99–100 (2004).
- Calabrese Barton S, Gallaway J and Antanassov P, Enzymatic biofuel cells for implantable and microscale devices. *Chem Rev* **104**:4867–4886 (2004).
- Katz E and Wilner I, *Handbook of Fuel Cells: Fundamentals, Technology and Applications*. Vol. 1: *Biochemical Fuel Cells*, ed. by Vielstich W, Gasteiger HA and Lamm A. Wiley, Hoboken, NJ, pp. 355–381 (2003).
- Schroder U, Nieber J and Scholz F, A generation of microbial fuel cells with current output boosted by more than one order of magnitude. *Angew Chem* **115**:2986–2989 (2003).
- Coates JD, Phillips EJP, Lonergan DJ, Jenter H and Lovely DR, Isolation of *Geobacter* species from diverse sedimentary environments. *Appl Environ Microbiol* **62**:1531–1536 (1996).
- Lovely DR, Analysis of the genetic potential and gene expression of microbial communities involved in the *in situ* bioremediation of uranium and harvesting electrical energy from organic matter. *OMICS* **6**:331–339 (2002).
- Bond DR and Lovely DR, Electricity production by *Geobacter sulfurreducens* attached to electrodes. *Appl Environ Microbiol* **69**:1548–1555 (2003).
- Hyun MS, Kim BH, Chang IN, Park HS, Kim HJ, Kim GT, *et al*, Isolation and identification of an anaerobic dissimilatory Fe(III)-reducing bacterium, *Shewanella putrefaciens* IR-1. *J Microbiol* **38**:206–212 (1999).
- Kim HJ, Park DH, Hyun MS, Chang IS, Kim M and Kim BH, Mediatorless fuel cell. US Patent 5 976 719 (1999).
- Kim HJ, Park HS, Hyun MS, Chang IS, Kim M and Kim BH, A mediator-less microbial fuel cell using a metal reducing bacterium *Shewanella putrefaciens*. *Enzyme Microb Technol* **30**:145–152 (2002).
- Park HS, Kim SK, Shin IH and Jeong YJ, A novel electrochemically active and Fe(III)-reducing bacterium phylogenetically related to *Clostridium butyricum* isolated from a microbial fuel cell. *Anaerobe* **7**:297–300 (2001).
- Pham CA, Jung SJ, Phung NT, Lee J, Chang IN, Kim BH, *et al*, A novel electrochemically active and Fe(III)-reducing bacterium phylogenetically related to *Aeromonas hydrophilia*, isolated from a microbial fuel cell. *FEMS Microbiol Lett* **223**:129–139 (2003).
- Tendler LM, Reimers CE, Stecher III HA, Holme DE, Bond DR, Lowy DA, *et al*, Harnessing microbially generated power on the seafloor. *Nature Biotechnol* **20**:821–825 (2002).
- Park DH and Zeikus JG, Improved fuel cell and electrode designs for producing electricity from microbial degradation. *Biotechnol Bioeng* **81**:348–355 (2003).
- Jang JK, Pham TH, Chang IN, Kang KH, Moon H, Cho KS, *et al*, Construction and operation of a novel mediator- and membrane-less microbial fuel cell. *Process Biochem* **38**:1–7 (2003).
- Rabaey K, Lissens G, Siciliano SD and Verstaete W, A microbial fuel cell capable of converting glucose to electricity at high rate and efficiency. *Biotechnol Lett* **25**:1531–1535 (2003).
- Cheng S, Liu H and Logan B, Power densities using different cathode catalysts (Pt and CoTMMP) and polymer binders (Nafion and PTFE) in single chamber microbial fuel cells. *Environ Sci Technol* **40**:364–369 (2006).
- Min B, Kim JR, Oh SE, Regan JM and Logan B, Electricity generation from swine wastewater using microbial fuel cells. *Water Res* **39**:4961–4968 (2005).
- Jiyoung L, Phung NT, Chang IN, Kim BH and Sung HC, Use of acetate for enrichment of electrochemically active microorganisms and their 16S rDNA analyses. *FEMS Microbiol Lett* **223**:185–191 (2003).